



# Mapping the danger to life in flash flood events adopting a mechanics based methodology and planning evacuation routes

Giovanni Musolino<sup>1</sup>  | Reza Ahmadian<sup>1</sup> | Junqiang Xia<sup>2</sup>  | Roger A. Falconer<sup>1</sup>

<sup>1</sup>Hydro-Environmental Research Centre, School of Engineering, Cardiff University, Cardiff, UK

<sup>2</sup>State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, China

## Correspondence

Giovanni Musolino, Hydro-Environmental Research Centre, School of Engineering, Cardiff University, Cardiff CF24 3AA, UK.  
Email: musolinogd@cardiff.ac.uk

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## Abstract

Extreme flood events are becoming more frequent and challenging due to climate change. Key objectives of this study are to evaluate different criteria used in assessing the hazard to people during flood events and, once determined, the most suitable method is then used to assess the hazard and the safest route(s) for evacuation during a flood event and for a particular case study. The results of the application of two criteria are analysed in terms of the flood hazard assessment with the two criteria being based on a widely used empirical approach and a mechanics based approach. Both criteria are used to assess the flood hazard to people during an extreme flash flood, which occurred on 16th August 2004 in Boscastle (UK). Results obtained for this study have highlighted that the mechanics based criteria are preferable in identifying the ideal escape routes, when considering the flood characteristics and the corresponding response of a human body. The main novelty of this study lies in linking the flood hazard rating with the human body characteristics, when determining the safest route and with a revised formula being developed, which includes the effects of ground slope in the application to a real case study.

## KEYWORDS

flash floods, flood evacuation route, flood risk management, flood hazard, flood modelling, human stability in floods, shock capturing models

## 1 | INTRODUCTION

Historically, river flooding is recognised as being one of the most devastating and frequently occurring natural disasters affecting the safety of people and communities. Studies have shown that risk due to floods is expected to be of even greater concern in the future, due to the combined effects of climate change, population growth and increased urbanisation into flood prone areas (Kvočka,

Ahmadian, & Falconer, 2017; Marchi, Borga, Preciso, & Gaume, 2010; Teng et al., 2017).

Following the definition of the American Meteorological Society, flash floods can be defined as those floods with a rapid rise and fall, with little or no advance warning, occurring usually as a result of intense rainfall over a relatively small area (Mariani & Lastoria, 2011; Modrick & Georgakakos, 2015). Possible flood events in basins small to medium size have a particularly rapid

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hydrological response, with the hydrographs that describe these events showing a short lag time. This means that the flow peaks are reached within a few hours, leaving a very short warning time or, in some cases, virtually no time at all. The typical rapid occurrence and high intensity of such flood events, over a relatively small geographic area, means that this type of flood can be particularly dangerous for the safety of people. It is estimated that 40% of the casualties due to flood events in Europe between 1950 and 2005 were caused by flash floods (Marchi et al., 2010).

Whilst it is impossible to reduce the flood risk for any river basin to zero, it is appropriate to reduce the risk associated with flooding as much as possible. Therefore, a key challenge for flood risk management is to minimise the impact of extreme flood events, despite the short time available for action. The main aspects therefore considered in reducing flood risk are: (a) determining the threshold of instability of people associated with the water depth and velocity in floods, (b) implementing flood mitigating defence schemes (both structural and non-structural), (c) developing emergency evacuation plans for flood events, and (d) informing and warning residents living in flood vulnerable areas about flood hazard and evacuation procedures (Bodoque et al., 2016; Borowska-Stefańska, Kowalski, Turoboś, & Wiśniewski, 2019).

Walking in flood waters can be extremely dangerous. People generally underestimate the force of the flow, even for shallow water depths, and it is therefore appropriate to design effective escape routes to minimise the risk to people. Regarding the stability of people in flood waters two different mechanisms have been explored and reported in the literature and there is general agreement about the two kinds of failure mechanisms, which include: sliding and toppling. Moreover, it is possible to recognise two main approaches to evaluate the stability of people in flood waters: the first based on an empirical or semi-quantitative criterion, and the second based on formulae derived from a mechanics based approach, and supported by experimentation.

An early study by Foster and Cox (1973) produced test results on the stability of children in flood waters, covering a range of different values for mass and height. The authors found that the stability of people in floods was determined through a combination of physical, dynamic, and emotional factors. In addition, this study showed that most of the stability failures occurred through sliding. Tests conducted by Abt, Wittier, Taylor, and Love (1989) demonstrated the importance of the toppling mechanism. Further studies with both adults and children have been undertaken by several authors (Jonkman & Penning-Rowsell, 2008; Karvonen, Hepojoki, Huhta, & Louhio, 2000; Takahashi, Endoh, & Muro, 1992), all of which

considered different clothing features and levels of expertise of the people, as well as different environmental conditions. The results from these experiments provided the basis for the development of an inversely proportional relationship between the mean flow velocity and water depth. However, the empirical approximation function is purely regressive and hence it is not possible to truly connect the hazard level and physical effects (Milanesi, Pilotti, & Ranzi, 2015). More recently, Martínez-Gomariz, Gómez, and Russo (2016) extended the work of Russo, Gómez, and Macchione (2013), and conducted tests on real people to derive hazard thresholds for pedestrians crossing streets. The thresholds were obtained through considering different combinations of footwear, visibility conditions and different age groups and the weight of people, with the results showing the importance of considering the size and weight characteristics of the respective human bodies.

Human instability in flood waters is a complex, but important, phenomenon. Due to the limitations of experimental studies involving people, conceptual models with different levels of simplification have been employed to estimate the instability of a human body as a function of the flow velocity and water depth.

Love (1989) simplified the human body to an equivalent rectangular solid body and studied the significance of the buoyancy force and its interaction with the toppling mechanism. Building on this study, Lind, Hartford, and Assaf (2004) represented the human body as a composition of different cylinders and developed three approximate mechanical models and two empirical models, based on available experimental data. Experimental results from Jonkman and Penning-Rowsell (2008) showed that the sliding mechanism was more dangerous than previous studies had suggested. Furthermore, they showed that the sliding mechanism first manifested itself when shallow depths and high flow velocities occurred, with this being the most likely scenario for flash floods in urban environments. Their simplified schematics for the mechanisms of sliding and toppling showed that the product of depth ( $h$ ) and velocity ( $v$ ), that is,  $hv$ , had a physical connection with the toppling mechanism, but that a better descriptor of the sliding mechanism was the product  $hv^2$ . Merz, Kreibich, Schwarze, and Thieken (2010) introduced resistance factors which depend on the characteristics of flood prone objects, as one of the parameters also being considered in assessing people stability in flood waters. These resistance factors describe the capability, or incapability, of an object to resist the impact of a flood. Also, mitigation measures, previous experience of flood events and early warning all influence the resistance factors.

Xia, Falconer, Lin, & Tan (2014b) developed a mixed approach using both a theoretical and experimental

analysis. In their work the authors conducted experiments on a scaled model of a human body, to help develop a parametric model for both mechanisms of toppling and sliding and considering the buoyancy force. Their model was calibrated using data available from the literature and their own experimental studies, which were undertaken for a range of slope conditions. The results from their work showed more conservative thresholds than those obtained through working with real people. This discrepancy was thought to be due to the fact that people can adjust their standing posture and orientation to best suit the direction of flow (Xia, Falconer, Guo, & Gu, 2014a). One of the advantages of their work is the significance of the characteristics of the human body in deriving human stability.

More recently Shu, Han, Kong, and Dong (2016) proposed a formula for the toppling instability of people in flood waters using a similar approach to that of Xia, et al. (2014b). The formula was derived from a mechanics based approach, complemented with flume experiments undertaken for two different sized 3D printed models of a human body. Furthermore, the authors accounted for grip strength, to take account of the ability of people to resist the forces of flood waters. Arrighi, Oumeraci, and Castelli (2017) proposed a mobility parameter for people walking in flood waters, which considers both the flood hydrodynamics and people characteristics. This parameter identifies a unique threshold of instability, depending on the local Froude number. Moreover, the authors discussed the hydrodynamic forces obtained from a 3D numerical model and experimental studies. Chen, Xia, Falconer, and Guo (2019), improved the work of Xia, et al. (2014b), by adjusting the toppling equation to take account of the key parameters, relative to the body characteristics of typical U.S. and European citizens.

Zhang, Zhou, Liu, Chen, and Wang (2016) presented an evacuation model based on the results from flood simulation studies, using the DHI MIKE model, and highlighting impassable flooded road using ArcGIS. Soon, Kamaruddin, and Anuar, (2018) analysed the psychological behaviour of people being evacuated during an unprecedented flood disaster in Malaysia in 2014 by using an empirical analysis. Guo et al. (2018) proposed an integrated model that included modules for predicting the 2D hydrodynamics, hazard degree for pedestrians, evacuation times, and the determination of ideal escape routes, but this study does not include the effects of ground slope in determining the flood hazard and evacuation route. Clearly the ground slope could affect the optimum evacuation route (González-Riancho et al., 2013). Moreover, values of the body height and weight are not included in the study using the method reported herein, which includes the Body Mass Index

(BMI). Zheng, Li, Jia, and Jiang (2019) proposed a modified flood model, integrating flood spreading processes with the determination of evacuation dynamics in underground metro systems, where the emphasis focused on water depth as the main driver. Four individual water depth thresholds, associated with pedestrian dynamics, were considered and analysed. Borowska-Stefańska et al. (2019) presented a model which included a GIS tool, using different algorithms available from the literature, to determine the optimal evacuation path and giving more credence to the road capacity and transport system during an evacuation.

With the exception of the work of Guo et al. (2018), the models above do not include any consideration of the stability of people in flood waters. This limitation has recently been recognised by several authors as a key aspect in Flood Hazard Assessment (FHA) (Arrighi et al., 2017; Kvočka, Falconer, & Bray, 2016; Martínez-Gomariz et al., 2016; Milanesi et al., 2015). As seen in this review, several aspects contribute to the complex phenomenon of flood waters, including physical and psychological parameters. The authors are aware of these independent components, but the scope of this research study has focused on the physical aspects and interactions between people and floods. Other aspects are planned for consideration in future studies.

Floods can also pose threats to human health (physical and psychological) (Jonkman & Kelman, 2005). During a flood event, one of the main causes of loss of life is drowning, which can occur whilst inside or outside of a vehicle (Doocy, Daniels, Murray & Kirsch, 2013; Jonkman & Kelman, 2005). The extensive review by Doocy, et al. (2013) also shows that there is a connection between geographical areas, gender and age with mortality during extreme flood events, hence, assessing the hazard to people can help to find the most critical population sub group vulnerable to flood hazard. This finding therefore enables early warning systems to be fine-tuned and for preparedness to be planned for flood response action.

As reported above, studies which take account of people stability along pedestrian evacuation routes in the event of floods have not previously been investigated in sufficient detail. Prior to this study, the main focus on other drivers of floods have been considered for people stability in flood waters, as recently reported by several authors (Arrighi et al., 2017; Kvočka et al., 2016; Martínez-Gomariz et al., 2016; Milanesi et al., 2015).

One of the main objectives of the present study is therefore to highlight possible improvements that could be made to FHA. This is achieved in two very different ways. Firstly, results from a widely used empirical method and a mechanics based and experimentally

calibrated method are analysed and compared, with both formulations being used to determine the Flood Hazard Rating (FHR) for pedestrian. Secondly, a novel methodology is presented, to identify preferred evacuation routes using the most recent methodology (i.e., the mechanics based approach), which is based on human body characteristics and the BMI. As has been pointed out also by Martínez-Gomariz et al. (2016) it is desirable to improve the FHA, especially for pedestrians, since pedestrians often have to move through cities at any time, and during any weather conditions, as highlighted in Rowe (2004). Hence, more research is required into the safety and stability of people when exposed to flood waters, so that more fundamental knowledge can be acquired to evaluate the associated flood hazard. The other objective of this study is to raise awareness about flood hazard to people, so that they do not underestimate the dangers of flood waters and, for different reasons, adopt a high risk behaviour (Figure 1); this behaviour results in them being more vulnerable to injury or even loss of life (Doocy et al., 2013). FHA is also found to be more impactful, and receives more attention, when presented

in the form of flood hazard maps (Koks, Jongman, Husby, & Botzen, 2015). Therefore, it is desirable to use a more scientific and physically based approach, such as the mechanics based method outlined herein, which considers different physical aspects of people moving in flood waters. This is particularly necessary when assessing the flood hazard to people based on data from flood hazard maps.

The main novelty of this work is therefore the implementation of a Lagrangian based FHA approach to determine the least hazardous evacuation routes, for people under the threat from flood waters. The proposed FHA method include the interactions between the flood and the human body characteristics and the local environment and highlights the danger posed to people due to a loss of stability in flood water. The other novel aspects of the study are the inclusion in the refined mechanics based methodology, of updated formulations compared to previous studies (i.e., inclusion of the effects of the ground slope) and also of updated human body characteristics and the use of BMI. These aspects are very relevant when considering the Department for



**FIGURE 1** People walking in flooded street during the Boscastle 2004 flood (a). HR Wallingford (2005) (b); (c) Rowe (2004)



the Environment, Food and Rural Affairs (DEFRA) and UK Environment Agency (EA) description of flood hazard, as given by the following quote: ‘flood conditions in which people are likely to be swept over or drown in a flood’.

## 2 | STUDY AREA

Boscastle is a picturesque village in Cornwall (UK), set in a long, narrow and steep valley, running down to a rocky entranced harbour and into the sea beyond (Figure 2).

On August 16th, 2004, during an extreme rainfall event, up to 200 mm of rain fell in approximately 5 hr (HR Wallingford, 2005). A flash flood affected Boscastle and caused severe damage to the village and its residents. People were rescued from rooftops and cars by helicopters (i.e., 100 people were airlifted to safety), six buildings collapsed due to the strong force of the flood water, over 70 properties were flooded, 79 cars were washed away into the harbour and one of the local bridges collapsed (Rowe, 2004). During the flood some roads were submerged by over 2 m of water (Xia, Falconer, Lin, & Tan, 2011a). Damage was estimated to be of the order of several million pounds.

Several factors contributed to this disaster, chiefly Boscastle's topography and morphology, combined with the tide and extreme meteorological conditions. Boscastle is located at the confluence of two valleys where the rivers Valency and Jordan meet; the whole catchment is extremely steep and narrow. When approximately 200 mm of rain fell within 5 hr (upon ground

that was already saturated due to several previous weeks of heavy rainfall; HR Wallingford, 2005), the water had nowhere to go but down the steep valley and into the harbour, that was already full at high tide. This combination of events made the perfect set of conditions for such an extreme flood event. Thus, both the basin and flash flood characteristics made Boscastle a perfect case study.

## 3 | NUMERICAL MODEL

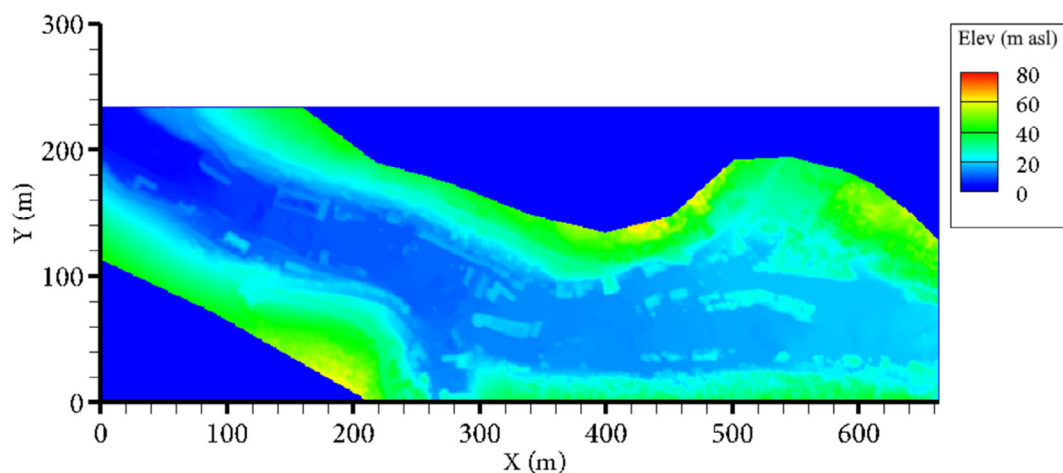
This study used the numerical model DIVAST TVD; a 2D hydrodynamic finite difference, fully conservative, shock-capturing model, that included a standard MacCormack scheme, in combination with a symmetric five point total variation diminishing (TVD) term (Liang, Lin, & Falconer, 2007a). DIVAST TVD has been developed to simulate complex hydrodynamics processes in river and coastal environments, by solving the shallow water equations for high Froude number conditions. This numerical scheme includes shock capturing, which means that it can capture discontinuities typical of trans or super-critical river flows (e.g., hydraulic jumps, bore waves, etc.). The shock capturing feature of DIVAST TVD makes this model ideal for modelling a short steep catchment, where a high Froude number, or trans-critical or supercritical, flows occurs. Traditional 2D models are unable to deal with such discontinuities, with the predicted results leading to numerical instabilities and inaccurate predictions of the flood characteristics. However, DIVAST TVD is highly suitable for simulating flash floods, storm surges, and all flood flow



**FIGURE 2** Picture of Boscastle, the river Valency and the harbour



**FIGURE 3** Boscastle study area



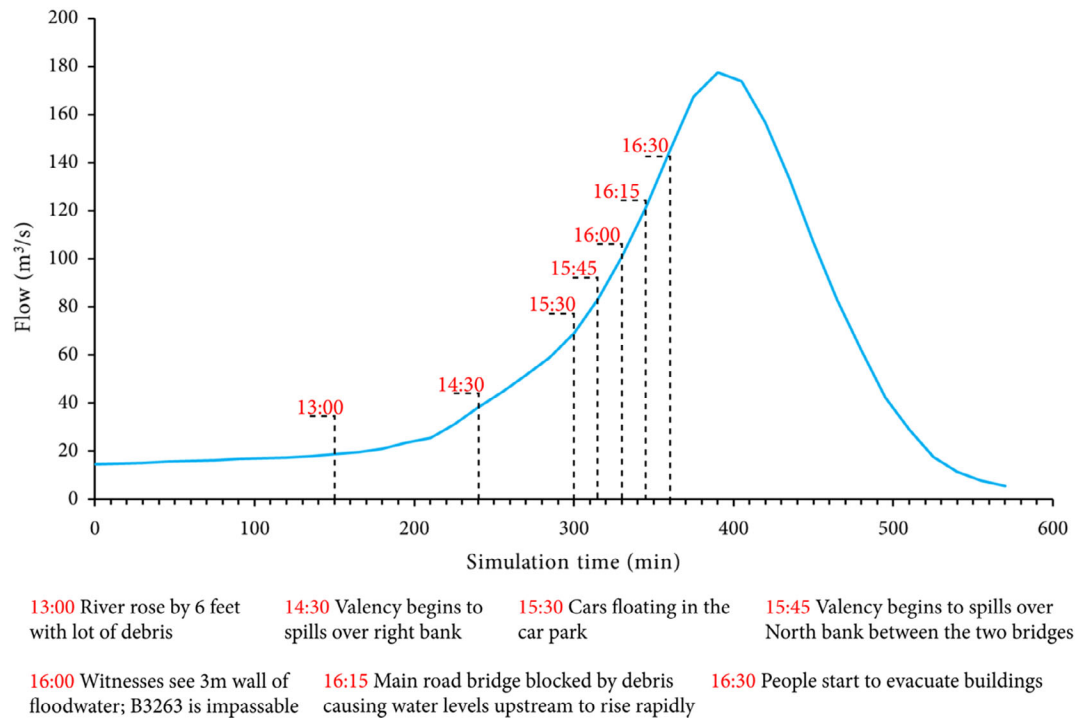
**FIGURE 4** Boscastle domain and topographic data

scenarios that involve rapid changes in the hydrodynamic conditions (Liang, Lin, & Falconer, 2007b). In the literature detailed information has been provided on the verification of the model relating to case studies using the DIVAST TVD scheme (Ahmadian, Falconer, & Wicks, 2018; Hunter et al., 2008; Kvočka et al., 2017; Liang et al., 2007a, 2007b; Neelz & Pender, 2013).

The domain analysed in this study was 235 m wide and 665 m long (Figure 3), which was divided into square cells, each with an area of 1 m<sup>2</sup>. Topographic data were collected through LIDAR, during a survey undertaken by the Environmental Agency and post the flood event (Figure 4).

A detailed report produced by HR Wallingford (2005), redacted after the flood event, provided the

basis for estimating the roughness characteristics across the domain. A constant Manning's roughness coefficient of value 0.040 was used across the whole domain (Kvočka, Falconer, & Bray, 2015). Calibration and validation of the model has been undertaken in some detail and has been reported previously (Falconer, Binliang, & Junqiang, 2012; Kvočka et al., 2015, 2017; Xia, Falconer, Lin, & Tan, 2011b). Also, the modelling performed by HR Wallingford (2005) to reconstruct the flood event, indicated that the peak discharge, located on the Valency just downstream of the confluence with the Jordan, was of a magnitude of 180 m<sup>3</sup>/s (Figure 5). The frequency of the flood event, using the FEH statistical and rainfall-runoff methods, was estimated to be of the order of 1 in 400 years (Roca & Davison, 2010).



**FIGURE 5** Hydrograph and timeline of the events: HR Wallingford (2005) and Environment Agency (2004)

The flow conditions are illustrated in Figure 6a–c, and it can be observed that generally the maximum velocities (Figure 6b) are greater than 1 m/s and the maximum Froude number (Figure 6c) is generally near to, or greater than, 1.

Figure 7 shows the location of both the Monitoring Points and Safe Points. Monitoring Points are points used to monitor the flood characteristics and the FHR at specific locations. Safe Points represent points where people can find shelter to wait for the rescue team to arrive. Safe Points were considered to be areas where flooding would not occur during the flood event and were chosen for this demonstration study based on the HR Wallingford report (i.e., flood maps, pictures of the flood event) on the 2004 Boscastle flood and confirmed by the modelling reported herein.

## 4 | METHODOLOGY FOR FHA AND DETERMINATION OF EVACUATION ROUTES

In this part of the study, two different FHA approaches have been considered. The first approach is an empirical method based on the work of Ramsbottom, Floyd, and Penning-Rowse (2003) and Ramsbottom et al. (2006), and the second is a more recent mechanics based method, based on the work of Xia et al. (2014a).

### 4.1 | Empirically based method

Ramsbottom et al. (2003, 2006) proposed a flood risk assessment approach that considers the likelihood of a flood, the probability of exposure to that flood event and the probability that people exposed to the considered event will be seriously, or even fatally, injured. This methodology has been developed for DEFRA and the UK EA. The authors tested several empirical formulae using laboratory and field experiments available in the literature, resulting in the following proposed empirical formula (Ramsbottom et al., 2006):

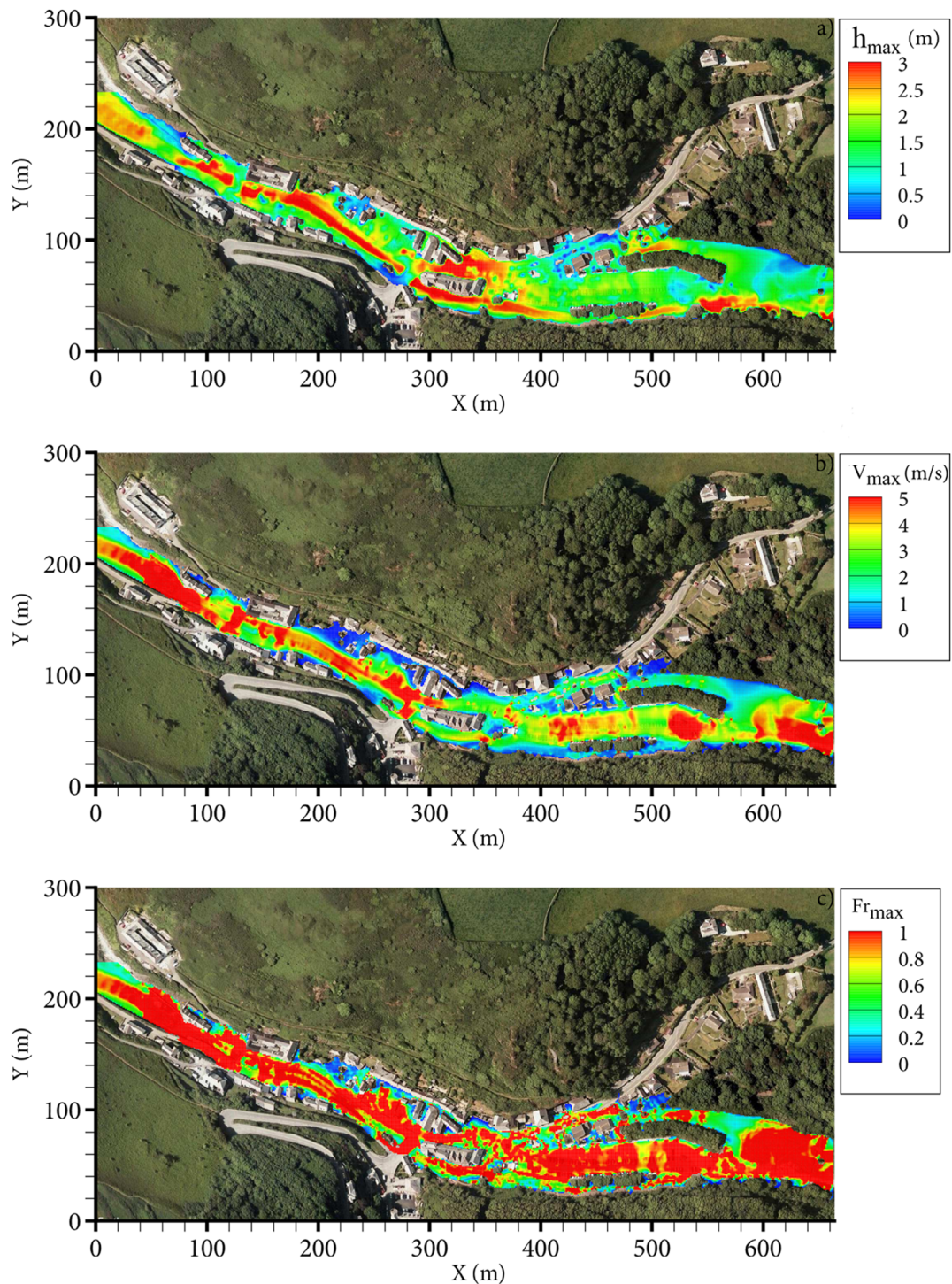
$$\text{FHR} = d(v + 0.5) + DF \quad (1)$$

where FHR = flood hazard rating value,  $d$  = water depth (m),  $v$  = velocity of the flow (m/s), and  $DF$  = debris factor that assumes values of 0, 0.5 or depending on the probability that debris will lead to a significantly greater hazard. Ramsbottom et al. (2006) proposed the flood hazard classifications reported in Table 1.

### 4.2 | Mechanics based and experimental calibrated method

Xia et al. (2014a) developed a stability criterion for a body immersed in flood water, for various ground slopes, by integrating a theoretical analysis and experimental



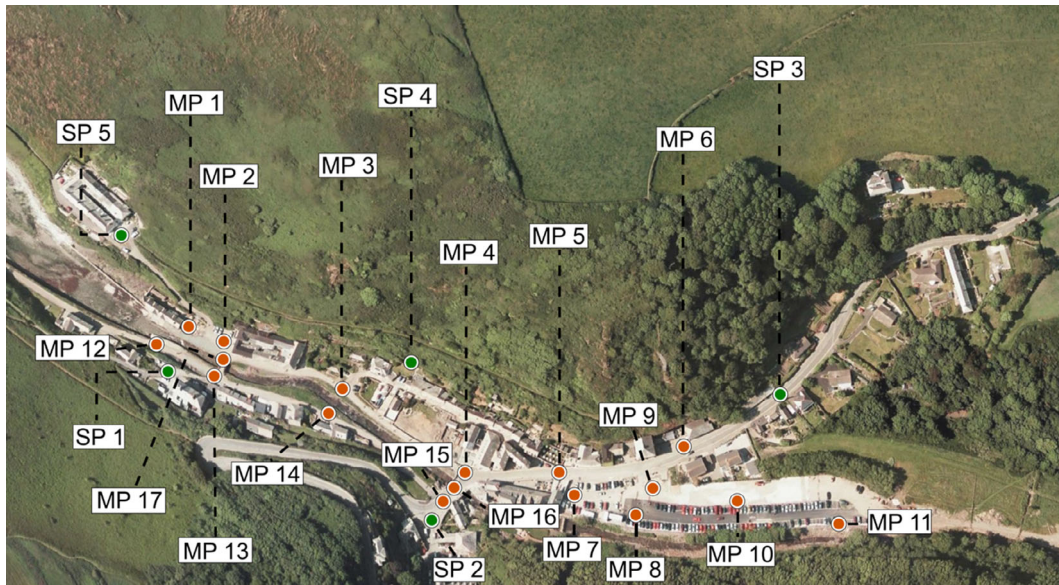


**FIGURE 6** (a) Maximum water depth ( $h_{\max}$ ), (b) Velocity ( $V_{\max}$ ), and (c) Froude number ( $Fr_{\max}$ ) for the study area

results to provide a calibrated mechanics based approach. The derived formulae considered both toppling and sliding failure mechanisms and included the effects of all forces acting on a people moving in flood waters (Figure 8). These forces included the: buoyancy force, frictional force, drag force, normal reaction force, and gravitational force. In addition, the authors included the effects of a non-uniform upstream velocity profile acting

on the human body, which moved on a horizontal or sloping ground in flood waters. Moreover, Xia et al. (2014a) included the impact of the net buoyancy force on a human body for the case of rapidly varying water depths. The experimental data collected during the tests in a flume, and the datasets available in the literature, were used to calibrate the parameters included in the formulae.

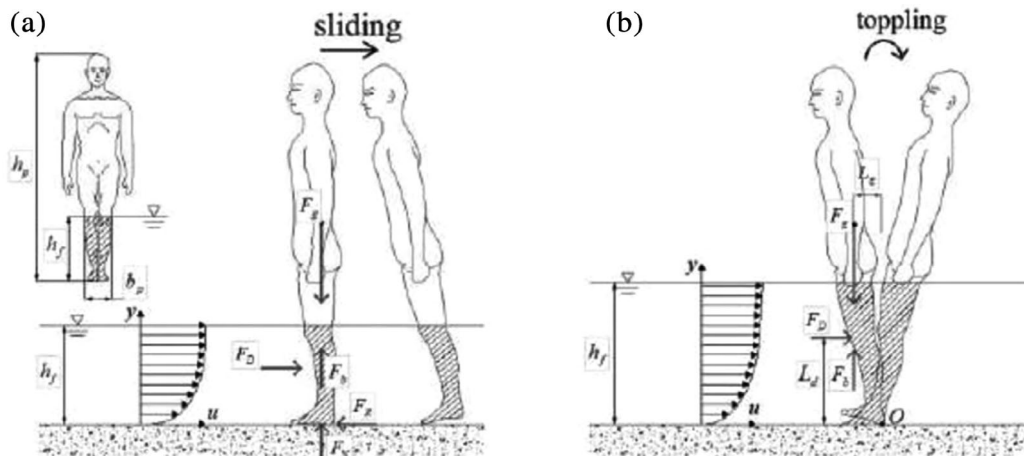




**FIGURE 7** Location of Monitoring Points (MP) and Safe Points (SP)

**TABLE 1** Flood hazard to people

FHR empirically based method	FHR mechanics based method	Description	
<0.75	<0.3	Low	Caution
0.75–1.25	0.3–0.6	Moderate	Dangerous for some
1.25–2.5	0.6–1.0	Significant	Dangerous for most
>2.5	>1.0	Extreme	Dangerous for all



**FIGURE 8** Forces acting on a flooded human body at instability for: (a) friction and (b) momentum by Xia et al. (2014b)

Xia et al. (2014a, 2014b) proposed the following formulae to determinate the incipient velocity, that is, the velocity at which a person loses stability in flood waters, for the case of slipping and toppling respectively.

The sliding failure mechanism is given as:

$$U_c = \alpha \left( \frac{h_f}{h_p} \right)^\beta \sqrt{\frac{m_p}{\rho_f h_p h_f} - \left( a_1 \frac{h_f}{h_p} + b_1 \right) \left( \frac{a_2 m_p + b_2}{h_p^2} \right)} \quad (2)$$

where  $U_c$  = incipient velocity (m/s),  $h_f$  = water depth (m),  $h_p$  = height of a person (m),  $m_p$  = weight of a person

(kg),  $\rho_f$  = density of water ( $\text{kg/m}^3$ ),  $\alpha$  and  $\beta$  = empirical coefficients, and  $a_1$ ,  $a_2$ ,  $b_1$ ,  $b_2$  = coefficients defining the characteristic features of a human body.

For a sloping terrain the toppling failure mechanism is given as:

$$U_c = \alpha \left( \frac{h_f}{h_p} \right)^\beta \sqrt{\frac{m_p}{h_f^2 \rho_f} (\cos\theta + \gamma \sin\theta) - \left( \frac{a_1}{h_p^2} + \frac{b_1}{h_f h_p} \right) (a_2 m_p + b_2)} \quad (3)$$

In addition to the parameters defined above,  $\theta$  = angle of the sloping ground (for flat terrains  $\theta = 0$ ) and  $\gamma$  = a correction constant; for further details about  $\gamma$  see Xia et al. (2014a).

At this point it is possible to evaluate the FHR for the different instability mechanisms using the following equation:

$$\text{FHR} = \text{MIN} \left( 1, \frac{U}{U_c} \right) \quad (4)$$

where FHR = flood hazard rating value,  $U$  = flow velocity, and  $U_c$  = incipient velocity, which is the minimum between  $U_{\text{toppling}}$  and  $U_{\text{sliding}}$ .

Regarding the values of the incipient velocity, two values were fixed by the authors. The first is for a water depth of zero, where the value of the incipient velocity was fixed as 25 m/s, otherwise the resulting calculations would lead to an error due to the division by zero. The second fixed value was 0.125/0.25 (i.e., 0.5 m/s), with this value being assumed by the incipient velocity when that part of Equation (3) under the root square sign was less than zero. This second fixed value represents the min value of the incipient velocity and is the one that gives the highest flood hazard, which means that it represents a critical state for the flood hazard.

The main differentiation between this mechanics based and experimentally calibrated method and most of the empirically derived flood hazard methods is the way the forces induced by the flood condition are considered. In the formulae derived using the empirical method, the overturning force applied to a body is proportional to the water depth times velocity (i.e.,  $H_f v$ ; Arrighi et al., 2017). In contrast, for the mechanics based method the overturning force is proportional to the water depth times the square of the velocity (i.e.,  $H_f v^2$ ). The consequence of this difference in the formulations is that higher velocities, and thereby momentum, have more relevance in the method proposed by Xia, et al. (2014a, 2014b) particularly

for high velocity flood flows. This aspect allows the method to be particularly suitable for conditions where sudden changes occur in the flood regime (e.g., extreme flood events, flash floods, etc.).

In considering the complex shape of a human body and its interaction with the hydrodynamics of a flood flow, the interaction depends not only on the flow conditions, but also on the portions and shape of the body that are in contact with flood waters (Arrighi et al., 2017). Hence, another relevant aspect of the mechanics based method is that it is possible to obtain precise stability thresholds for a population that live in different geographic areas or countries (e.g., Europe, America, Asia, etc.), as well as considering the population's sub categories (e.g., male, female, children, elderly, etc.; Kvočka et al., 2016; Milanese et al., 2015).

The characteristics of a specific body type are described by the coefficients  $a_1$ ,  $b_1$ ,  $a_2$ , and  $b_2$ . Values for these parameters can be evaluated from the typical features of a human body, such as: height, mass and volume, as well as the mass of the body segment parameters (such as: legs, arms, torso, etc.). Further details about these coefficients can be found in Xia et al. (2014b). The parameters  $\alpha$  and  $\beta$  are based on calibration of the mechanics based method. These two parameters depend on the shape of the tested human body, the ability of the person to adjust their position to resist sliding or toppling in flood waters, and the drag and friction coefficients between the person and the ground surface. Values for  $\alpha$  and  $\beta$  are different for various body types and for toppling and sliding mechanisms. Due to a lack of available data for typical U.K. body characteristics, the parameters used in this study were based on those values reported in the study by Xia et al. (2014b), where the following values were used:  $a_1 = 0.633$ ;  $b_1 = 0.3667$ ;  $a_2 = 0.001015 \text{ m}^3/\text{kg}$ ;  $b_2 = -0.0004927 \text{ m}^3$ ;  $\alpha_{\text{toppling}} = 3.472$ ;  $\beta_{\text{toppling}} = 0.188$ ;  $\alpha_{\text{sliding}} = 7.975$ ;  $\beta_{\text{sliding}} = 0.018$ . For the data relative to height and weight, see Section 5.2.

As seen in Table 1, the method used by DEFRA classifies the FHR into four categories. In contrast, the mechanics based and experimentally calibrated method classifies the flood hazard using the principle of bivalence, that is, the hazard state is either true or false. This means that there is only a single threshold value defining the stability of a person in flood waters. In order to allow for a more precise and meaningful comparison with the DEFRA method, the results for the FHR using the mechanics based method have also been split into four categories. In doing so two more categories have been added to the mechanics based method, including 0.3 and 0.6 (Kvočka et al., 2016). This results in the mechanics based method also having scope for classifying

the stability of a human body in flood waters as reported in Table 1.

In summary, the mechanics based method takes account of the key physical parameters affecting the stability of a person in an extreme flood event, including: (a) bed slope, (b) all physical forces acting on a human body in flood waters, (c) more sensitivity to variations in the velocity, and (d) adaptability to different body types (e.g., age groups). Thus, a critical velocity is calculated for a specific water depth, which means that at a specific depth a human body would start to lose stability if the velocity is higher than the threshold, represented by the corresponding critical velocity. In this way a large depth and low velocity of flow, would not necessarily be classified as hazardous, especially if the flow velocity is smaller than the critical velocity.

Using the mechanics based method also takes account of different body characteristics, which can vary in different parts of the world. This leads to a more scientific approach in comparison with the empirical assessment, which therefore leads to a more credible result in assessing the safety of people and socio-economic assets and investments, since a quantifiable FHA is crucial for emergency response, resilience planning and mitigation schemes, including insurance (Trigg et al., 2016; Svetlana, Radovan, & Ján, 2015).

### 4.3 | Role of body mass index in parameter's determination

In this section the role of BMI is examined in determination of the parameter  $h_p$  (height in m) and  $m_p$  (weight in kg) necessary to determine the flood hazard by using the mechanics based method. This extension to this method will enable the design of evacuation routes best suited to meeting the needs of the most vulnerable users, for

example, elderly adults or children. Using the BMI to determine the parameters  $h_p$  and  $m_p$  is another novelty of this work and allows for the determination of more realistic evacuation routes, tailored for the population living in the study area. Using this approach, it is possible to have a medical/scientific based approach in the choice of the weight of a person, once their height is defined according to the country and population sub-category. In Section 5.2 the analysis relative to the influence of height and weight parameters is reported in determining the evacuation routes.

The BMI is defined by WHO as the person's weight in kg divided by the square of the person's height in metres ( $\text{kg}/\text{m}^2$ ; WHO Expert Committee on Physical Status, 1995). The lowest BMI for a healthy adult over 20 years of age is 18.5. Thus, the BMI chosen for adults is 18.5 in order to consider the most vulnerable person in the normal weight category. In other words, ensuring the safety of the most vulnerable person in this category will ensure the safety for other persons of the same category. Data are available online at WHO Global Database on BMI.

Adult and children weight/height values are reported in Tables 2 and 3.

### 4.4 | Determination of evacuation routes

The routes to the Safe Points, which pose the minimum danger to life, have been selected as the evacuation routes based on the FHR being linked to the pedestrian characteristics, with this being one of the novel aspects presented in this study. Since the empirically based method does not allow the pedestrian characteristics to be considered, the FHRs derived from this latter method have not been considered in the determination of the evacuation routes.

**TABLE 2** Weight/height values for adults

Adults class	1	2	3	4	5	6	7
Height (cm)	160	165	170	175	180	185	190
Weight (kg)	47.36	50.37	53.47	56.66	59.94	63.32	66.79

**TABLE 3** Weight/height for children and young people

Children/teenagers class		1	2	3	4	5	6
Boys	Height (cm)	109	127	143	161	176	177
	Weight (kg)	16.2	26	35	50	67	69.5
Girls	Height (cm)	109	127	144	159	163	163
	Weight (kg)	17.2	26	36	50	57.5	58
Age	Years	5	8	11	14	17	20



The representative human categories for the area of the study were first identified and the relevant parameters, namely,  $h_p$  and  $m_p$ , were determined. The FHR for the whole domain was then predicted for the event duration, based on the mechanics based method, as presented in Section 5. The FHR approach was then used to rank the Monitoring Points.

People were then considered to move from each point in all possible directions towards Safe Points. The maximum FHR for each route was recorded and the route with the lowest maximum FHR was selected as the safest route. A few Monitoring Points have been selected along the routes for this study site, in order to demonstrate the methodology. The accuracy of the method can be improved by increasing the number of the Monitoring Points.

If an area was characterised by the presence of children, elderly people or a mixed population of children and adults (e.g., an area including schools, hospitals, etc.), then the children category was deemed to be most

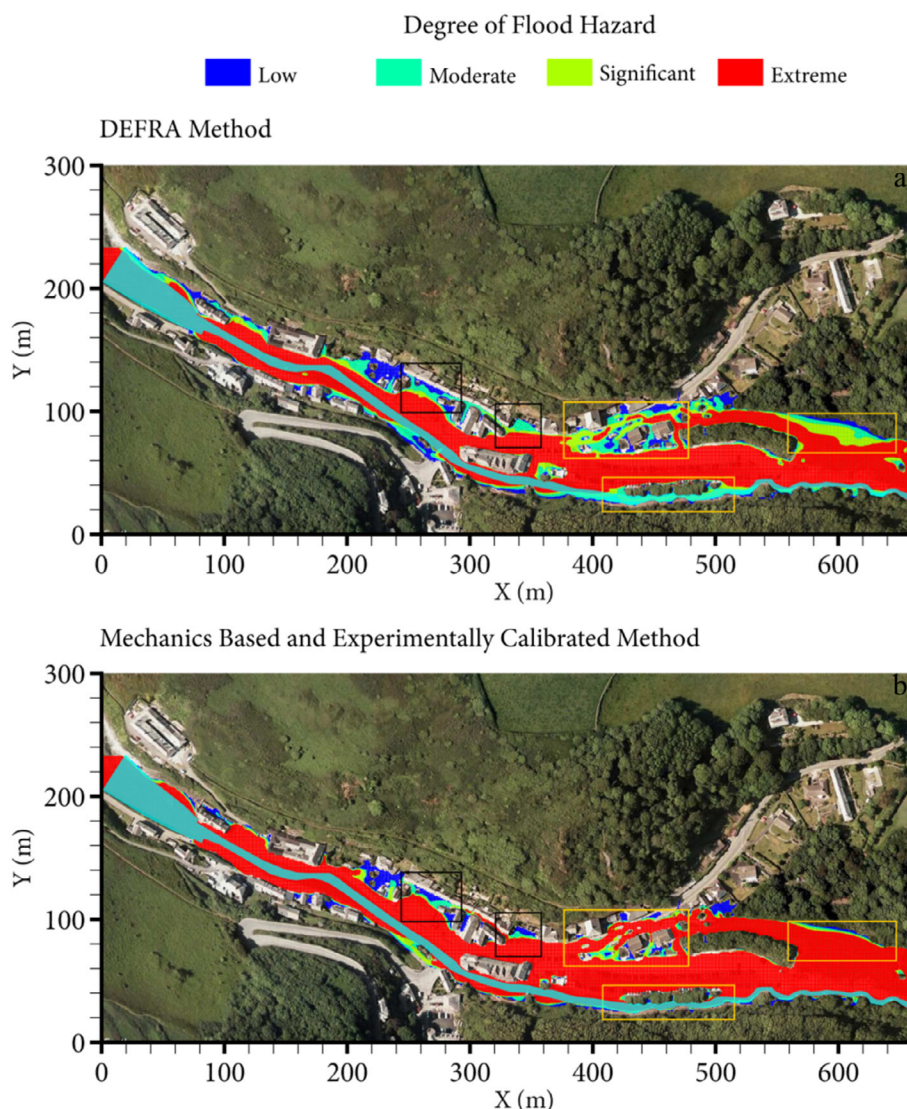
significant and was used to determine the preferred evacuation route. For areas such as industrial, offices or generally places characterised only by the presence of adults, then the preferred escape route was determined using only the critical adult category.

In general, it is possible to consider the body characteristics relative to different geographic areas, thereby tailoring the escape plan according to the physical characteristics for different regions, that is, with mainly height and weight being considered, as shown in Section 5.

## 5 | RESULTS AND DISCUSSION

### 5.1 | Flood Hazard Rating

Figure 9 shows a comparison between the FHR predicted by the methods outlined herein. For this comparison an average British male, with a height of 1.75 m and a



**FIGURE 9** Comparison of the FHR: (a) DEFRA method and (b) mechanics based method, with the black and yellow rectangles illustrating examples of the difference in the results



weight of 83.6 kg (ONS—Office for National Statistics (UK)) have been considered. The FHR for all the other categories used in Section 5.2 were calculated and showed similar differences and have therefore been reported in Appendix which is available as supplementary material.

Results from the mechanics based method result in a larger area with a higher FHR when compared to the results obtained using the DEFRA method (an example is given in the yellow rectangles in Figure 9). The results reported in Figure 9 show that the difference in terms of red areas (FHR = Extreme) is 32% more when using the mechanics based method (i.e., the two maps have been compared and the differences of red areas has been quantified in percentage terms). The reason for this difference is that the mechanics based approach is more influenced by the flow conditions, particularly at higher velocities and with the risk being linked to the square of the velocity times depth. In contrast the DEFRA approach is to link the hazard to the velocity times the depth. This approach is inconsistent with an analysis of the hydrodynamic forces on a stationary body. The differences in the results are generally covered by experimental coefficients at low velocities. However, for this case the differences in the hazard assessment are expected to be considerably higher when the velocity is well in excess of unity, as is the case for most extreme flood events, particularly since the force is the square of the velocity. Thus, in assessing extreme flood events such as flash floods, which are generally characterised by deeper floodwaters, higher flow velocities and sudden variations in the flow regime lead to the necessity to include a full physical analysis, as for the mechanics based approach and in order to generate more reliable FHRs (Arrighi et al., 2017; Kvočka et al., 2016; Milanese et al., 2015).

Also, the differences in the results between the two methods can be attributed to a number of limitations observed in the empirical method. Firstly, the empirical approximation functions do not connect the hazard assessment with the physical characteristics of people, and so on; for example, there is no differentiation in the threshold levels between children and adults (Milanese et al., 2015). Furthermore, and as pointed out by Cox, Shand, and Blacka (2010), the weaknesses in this empirically based approach are three-fold. Firstly, the limiting flow regimes extrapolated from the datasets averaged and used as data by Ramsbottom et al. (2003, 2006), were affected by the training gained during the experiments (i.e., by becoming experienced in walking in flood waters through the repetition of the experiments). Due to the averaged data, the final formula includes the effects of training in formulating the results. However, this assumption is not valid for

the general case, since most people do not have any experience as to how they should move in flood waters. Secondly, no upper depth limit is considered by the authors, which means that a large depth and a low velocity would not necessarily be considered as dangerous, but this may not be the case since once the person starts to float (i.e., the person is unstable), then their safety depends upon the ability of the individual to swim. Thirdly the debris factor proposed is not supported by robust experimental evidence.

The DEFRA approach was the first of its kind at the time of its introduction and has contributed significantly to flood risk management since 2003. As Ramsbottom et al. (2003) pointed out in their work, the expression they proposed 'is based on experience of flood hazard estimation. It is recognised that the expression appears rather arbitrary and refinement of this relationship is proposed in Phase 2, based on a more detailed assessment of previous work together with possible new research'. In Phase 2, Ramsbottom et al. (2006) refined the expression, but only for the part relative to the debris factor, because at the time studies relative to the use of the square of the velocity were not available.

Another aspect to consider is that the DEFRA method assessed a higher FHR compared with the mechanical based method, in areas characterised by relatively smaller velocities and deeper floodwater (i.e., black rectangles in Figure 9). This difference in the results is explained remembering that in the DEFRA method the flood hazard is defined as a function of the product depth times velocity as mentioned above.

The differences in results from the application of the two methods suggest that more experimental work it is necessary to properly assess the results obtained from the two method and contribute to improve more FHA. Since an under-estimation of high-hazard areas imply first people's safety but as well social and economic impacts, since development of an area can be influenced by FHA especially when considering people's safety. As well an over-prediction of hazard could alter the design of the safest evacuation route or have economic impacts when flood defence schemes have to be designed.

All the considerations reported above suggest that a mechanics based method provides more insight, details and a more physically robust approach when compared with the methodology adopted by DEFRA. For this reason such a methodology should be preferred to the empirical methods used to assess flood hazard especially for the case of extreme flood events, with similar findings being reported by others in the literature (Kvočka et al., 2016; Milanese et al., 2015).

**TABLE 4** Variability of FHR with height and weight

Monitoring Point	FHR—boys 2	Monitoring point	FHR—adults 1	Monitoring point	FHR—average adult
4	44.31	4	44.31	4	44.31
2	43.22	10	32.58	10	32.58
10	32.58	13	31.63	13	31.63
13	31.63	7	26.68	7	26.68
7	26.68	3	26.59	3	26.59
3	26.59	8	26.59	8	26.59
8	26.59	1	23.2	1	23.2
1	23.2	5	19.93	5	19.93
5	19.93	14	17.5	14	17.5
16	18.94	2	16.69	2	11.57
12	18.81	16	10.62	16	7.61
14	17.5	17	9.06	17	6.86
11	12.49	11	8.59	11	6.37
17	12.12	12	8.26	12	6.05
6	7	6	4.37	6	3.18
15	2.6	15	1.97	15	1.5
9	0.78	9	0.38	9	0.24

Note: The green colour is used when the Monitoring Point has the same rank for two or more human categories, otherwise the colour is orange. Light blue is used if the Monitoring Point for two or more human categories has the same rank position but a different value of FHR.

## 5.2 | Analysis of the influence of different heights and weights

In this section, the influence of the weight and height parameters of the flood hazard for adults and children as obtained using the mechanics based approach have been analysed and are discussed herein. Table 4 highlights the results of the FHR at the peak flood time, based on data from 17 monitoring sites. The characteristics related to these categories are shown in Tables 2 and 3 and the location of the Monitoring Points are shown in Figure 7. Only three sets of results are reported herein to avoid repetition, with similar results having been obtained for all of the Monitoring Points, for the whole simulation period, and for the various human categories. The values may seem high, but the data reported are the maximum values for the entire event for the Boscastle flood and were expected to be high at the peak of the event.

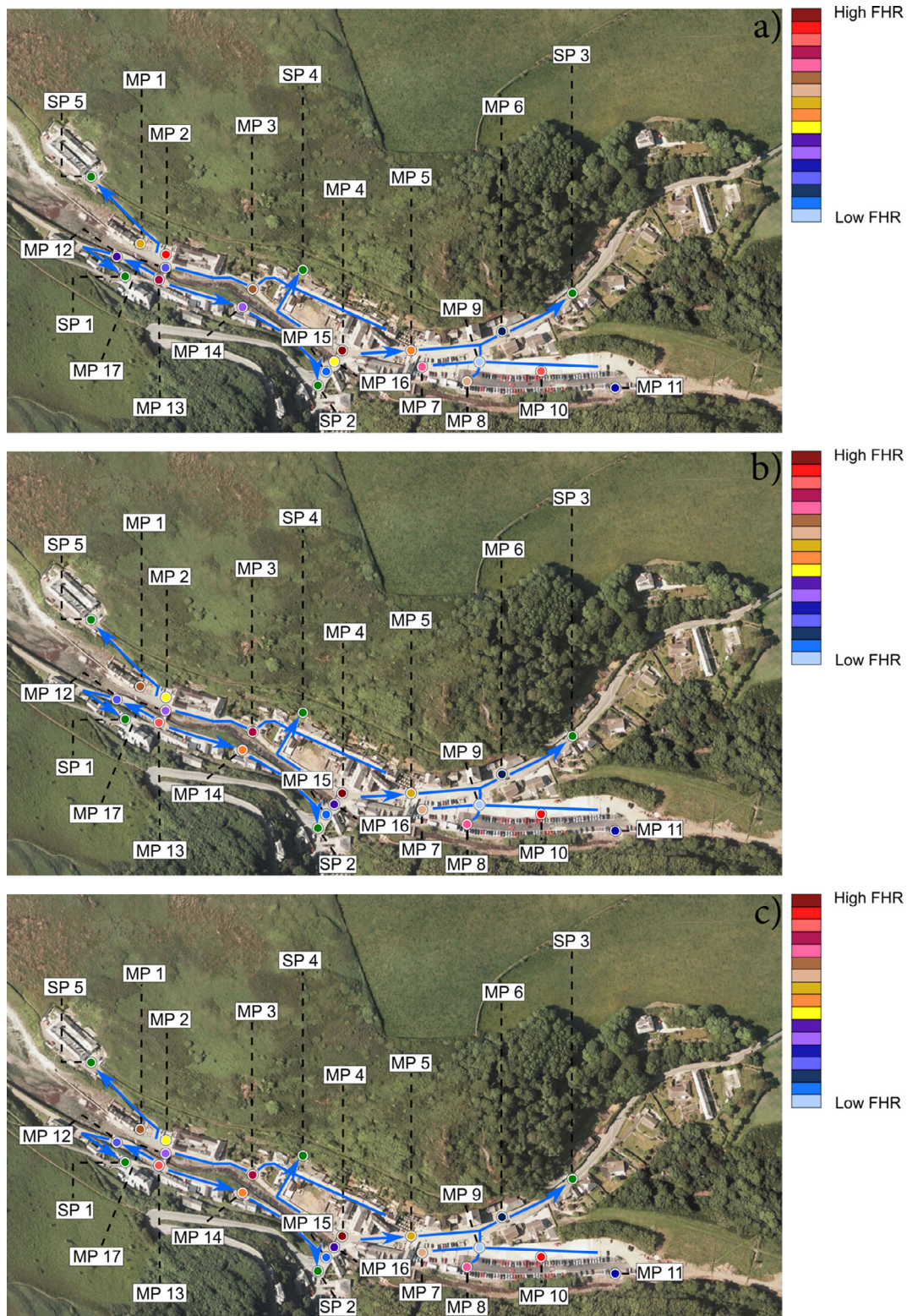
From the results, reported in Table 4, it is possible to note the influence of the height and weight of a person in terms of the FHR for the most representative categories. In Table 4, a Monitoring Point is coloured in green if the Monitoring Point has the same rank for two or more human categories, otherwise it is shown in orange. If the Monitoring Point for two or more human categories have the same rank position, but have different values of FHR,

then the cell is coloured in light-blue. The results in terms of the FHR are reported from the highest to the lowest, for all the 17 Monitoring Points. Between the categories of Boys 2 and the two adult categories there is rank agreement only for Monitoring Points 4, 6, 11, 15, and 9. Also, the Monitoring Points 6, 11, 15, and 9 have the same rank in terms of hazard rate, but they show different values of the hazard rate when the influence of weight and height is taken into account. This shows the importance of the body characteristics in determining the FHR and consequently the evacuation route.

The two adult categories are almost in agreement in terms of rank. Monitoring Points 2, 16, 17, 11, 12, 6, 15, and 9, show the same rank, but different values for the hazard rate due to the influence of weight and height are observed, as mentioned above.

Figure 10 shows optimal evacuation plan for the categories of: 'average adults' (Figure 10a), 'adults 1' (Figure 10b), and 'boys 2' (Figure 10c). Figure 10a,b shows the same FHR for all the Monitoring Points, as also reported in Table 4, where it is highlighted that despite the fact that monitoring points have the same ranking, the FHR values are different for almost half of the Monitoring Points. This is explained by the differences in height and weight between the two adult classes. Figure 10 c shows how considering the critical category





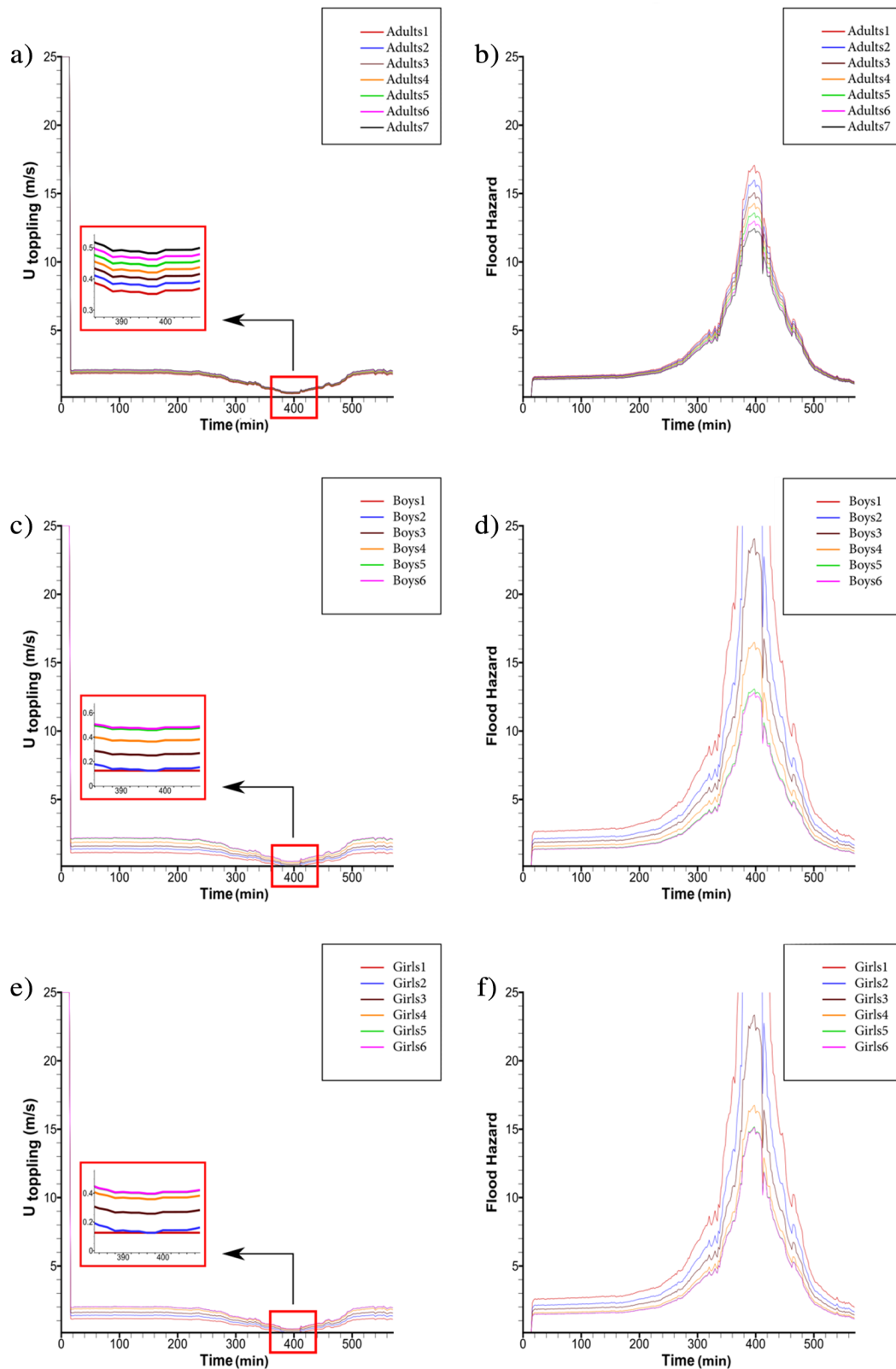
**FIGURE 10** Location of Monitoring Points (MP), Safe Points (SP), and evacuation routes (blue lines) for: (a) boys 2, (b) adults 1, and (c) average adults

for children leads to changes in the FHR values for almost all the cases, as illustrated in detail in Table 4.

Figure 11 shows detailed results for Monitoring Point 2, reporting the incipient velocity for toppling

instability and the relative flood hazard (with these results governing the critical conditions for this case, and with the sliding results reported in Appendix), results for other Monitoring Points are reported in

## Monitoring Point 2



**FIGURE 11** Velocity for toppling mechanism and flood hazard for Monitoring Point 2

Appendix. In all cases it can be noted that as the weight/height value increases then the critical velocity also rises, thereby leading to a corresponding reduction

in the flood hazard. Figure 11a,c,e shows that at the same location (i.e., Monitoring Points 2) there is a difference of approximately 1 m/s between the incipient



velocity for adults and children or young people. This relatively large difference between children and adults should be carefully considered, since at Monitoring Points 2 the incipient velocity for the adults (Figure 11a) never reaches the critical state (i.e., a value of 0.5). Therefore, this point is expected to be safe for this category. However, when children and teenagers are considered, this point becomes unsafe for the first two classes, that is, for both boys (Figure 11c) and girls (Figure 11e), as the velocity is higher than the critical velocity for these categories. As reported in Table 4, for the category Boys 2, Monitoring Points 2 is ranked as the second highest FHR, while the rank of this point drops to 10th for the two adult categories.

The results reported and discussed in this section show that attention needs to be particularly focused on these findings where they are at, or close to, more vulnerable categories, such as where schools, sport centres, and so on exist, and where children are more likely to be present. This is because the threshold of incipient velocity is lower than the corresponding value for adults. For elderly people the same consideration would apply as for children (Milanesi et al., 2015; Xia et al., 2014b).

For this particular case study, the ideal evacuation routes were therefore calculated for children, since children were expected to live in the village.

## 6 | CONCLUSIONS

The work considered herein reports on assessing the stability of human bodies in flood waters during a flash flood event using two different approaches, and provides a novel methodology for the determination of escape routes, based on considering the characteristics of a human body and the BMI. The first method is a widely used empirical method, and the second is a mechanics based method, supported with experimental calibration. The aim of this paper is not to question any method currently used by authorities and practitioners, but to point out that there is still a need to improve on the assessment of flood hazard, especially when considering flash floods and extreme events.

A comparison of the results based on using the two methods suggests that the mechanics based method, coupled with a methodology which considers the human body characteristics and BMI, should be preferred to the empirically based method. This finding is particularly relevant in terms of identifying preferred escape routes and in assessing the hazard for flash floods, and particularly for extreme events. This is because the first method can account for all factors necessary to describe the highly

complex phenomenon of human instability in flood waters, especially for the case of flash floods. These factors would include considering all of the physical forces acting on a human body, interacting with flood waters. These considerations lead to a more physics based approach when considering the analytical approach, supported with experimental studies, with the predictions being more reliable, robust and generic in comparison with empirical predictions. More reliable predictive results improve the FHA, not only in terms of the safety of people in floods, but also in terms of the socio-economic impact.

Another benefit in assessing flood hazard with a mechanics based approach is that it allows the analysis to be tailored to include the characteristics of a specific body type, such as age group, tall, small, and so on. As shown in the results reported herein, the planning of flood escape routes needs to be considered and adapted for different body types, particularly since the characteristics of the human body can vary significantly from one country to another, often leading to different stability thresholds. Furthermore, a more specific characterisation can be undertaken when considering adults, children and elderly adults etc. As can be seen from the results, when the body characteristics are considered for different human categories, then in order to guarantee safety for all in planning the preferred escape route then the most critical class must be considered.

Although various formulations conclude that deep water would always be dangerous, in contrast shallow, fast flowing flood water can be just as dangerous and even potentially more dangerous, especially in urban environments. This aspect must be kept in mind in the design of evacuation plans, but also it is important to raise awareness of this aspect with flood planners, and so on, since the hazard of fast flowing shallow flood waters can often be underestimated. Being aware of flood escape routes and the most appropriate response of people in extreme flood events should ensure a reduced risk of serious injury or even fatality during such events.

This study has demonstrated that there is still scope to improve on the formulations for assessing flood hazard, especially for the mechanics based method with the human body characteristics being included; with this aspect not having previously being included. This study further demonstrates the importance of developing useful tools, for the design and planning of evacuation routes based on the requirements applicable to the most vulnerable category. Further research is needed to assess human body behaviour in flood waters, with this being an important factor in further improving the accuracy of FHA.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## ORCID

Giovanni Musolino  <https://orcid.org/0000-0002-6273-5630>

Junqiang Xia  <https://orcid.org/0000-0001-7613-3457>

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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